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An Evaluation of System Modularity and Interface Standards as a Means for Continued Platform Level Relevance

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ABSTRACT

This paper will develop a descriptive working definition of modularity regarding ship systems. An effort will be made to expose the underlying motivation and attractiveness of modularity in naval vessels utilizing economic salvage value and continued operational relevancy. A survey of 50 years of modern system development in support of modularity will be supported by a historical case study. The historical analogy will focus on the concurrent development of platforms and weapon systems during the age of sail. Specific focus will be given to platform developments and the advent of marine artillery and their associated technological development. The insight developed will then be applied to two modern naval corollaries.

KEY WORDS

Modularity, Naval Design, Weapons Systems, System Design, Decoupled Architecture

MOTIVATION

The first section of this paper will develop a descriptive definition of modularity along six continuums: 1) Componentization, 2) Architecture, 3) Configurability, 4) Flexibility, 5) Interface Points, and 6) Allocation. An effort will be made to expose the underlying motivation and attractiveness of modularity in naval vessels utilizing economic salvage value and a less tangible ship effectiveness. Finally, the first section concludes with a look at investment duration by project for the last five decades relating to the development of architectural standards and why many modern modularity efforts have failed to produce the envisioned results.

The second and third section of this paper develop a historical analogy and review modern corollaries, respectively. The historical analogy will focus on the concurrent development of platforms and weapon systems during the age of sail. Specific focus will be given to platform developments and the advent of marine artillery and their associated technological development. The final section presents two modern modularized naval vessels and will assess their success of integrating modularization, considering these historical lessons learned.
It is the goal of this paper to illuminate several critical factors in determining the success or failure of a modularization effort on the scale of a modern naval vessel. To this end, this discourse is driven by four motivational questions:

1. What is the allure of system level modularity for ships?
2. How does an architectural standard develop to support sustained modularity?
3. Why have modularity efforts failed to date?
4. What can we learn from historical implementations of modular system architectures in the marine environment?

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MODULARITY DEFINITION

Let's begin our analysis of system level modularity and impact that it potentially may have on a modern naval vessel with a standardized definition set. What exactly is modularity? We will double back to the guiding questions outlined in the motivation once we establish a baseline vernacular. To begin with modularity is an imprecise term. As such it has a multitude of meanings dependent upon the context of the discussion. (Kubota et al., 2017; Schank et al., 2016) For the purposes of this discussion, I would like to define modularity along six continuums: 1) Componentization, 2) Architecture, 3) Configurability, 4) Flexibility, 5) Interface Points, and 6) Allocation. While several of these concepts are potentially understood I will expand upon each to maintain clarity.

1. Componentization is the degree to which the end unit system is comprised of segregable subunits. This concept is the underpinning of modern software development approaches, define a self-contained reusable block of code that is insulated from changes in the rest of the stack. (Baresi & Miraz, 2011) For this discussion which is focused upon hardware systems componentization will range from *sparse* to *prevalent*.
2. Architecture is the degree to which new components can be integrated into the overall system. (Elmenreich, 2007) An architecture can assume values between *closed* to *open*. Theoretically in a completely open architecture any new component could be easily incorporated into the existing system. This does have some limitation in application.
3. Configurability is the degree to which subsystems and components can be dynamically arranged. (Balka & Wagner, 2006) Configurability can be scored on the continuum from *unconfigurable* to *adaptive*. It is important to note that each new configuration needs to function for an intended purpose.
4. Flexibility can be considered the number of functional uses for a single component or subsystem. (Lafou et al., 2016) Flexibility is scored between *limited* to *versatile*. While higher levels of flexibility are typically a good thing, the versatility of an object typically comes at the expense of another system attribute.
5. Interface points are either *customized* or *standardized*. One might be wondering what the gradation between these end points. An example of an interface point that is partial standardized and partially customized would cell phone chargers or USB 2/3 A-plugs. While the form factor is the same the power and data rates vary greatly depending on the standard that is being employed.
6. The final continuum definition has to do with the system level allocation or more specifically the requirement that is being addressed with this subsystem, this value can be assessed between *single use* to *multipurpose*.

While this six-vector scoring system is not likely to incorporate all the features that a designer would be concerned about during the integration of a complex system, it does begin to outline some of the major factors for the consideration of modularity and the influence of that modularity upon the rest of the ultimate system. Some notable exceptions would be system level mission effectiveness, space and weight considerations, and ultimately total system level cost. Now that a vernacular has been developed let's revisit the motivation and explore some recent efforts in sustaining system level modularity.

WHAT IS THE ALLURE OF SYSTEM LEVEL MODULARITY FOR SHIPS?

As highlighted in the prior example the cost versus capability of an upgrade in context with the service life of the total system creates the trade space for a modularity reasonableness assessment. If you consider the traditional economic concept of salvage value in conjunction with the fact that a ship is not a singular end system but truly a system-of-systems, the modularity of the subsystems becomes an imperative for continued operation.

First let's address the concept of asset depreciation and salvage value. The basic formula for calculating salvage value of an asset can be found in any engineering economics textbook or various other sources. (Eschenbach, 2011) Equation 1, below represents a simple declining balance depreciation approach.

$$S = P(1 - i)^y \qquad [1]$$

The salvage value, S, is the product of the present value of the asset, P, and value retention rate, $(1 - i)$, raised to the number of years, y. If one begins with a present value of \$1B and applies a constant depreciation schedule (DBD) of 10% annually (*TR 2021/3*, 2021) the salvage value is approximately \$42M at the end of 30 years or 4.2% of the initial value. However, if one applies a compounding custom schedule depreciation (CSD) behaving similar to Moore's Law that doubles every decade, the salvage value is nearly \$200K or 0.02% of the initial value.

The custom schedule depicted in CSD data presented in Figure 1, applies a 10% depreciation for the first decade, a 20% depreciation for the second decade, and a 40% depreciation for the third decade. This acceleration in depreciation can be largely attributed to vessel wear and tear and system level obsolescence. The accelerated rate of obsolescence and depreciation is particularly applicable to military vessels, a bulk carrier would not be as dramatically affected by technology modernization.

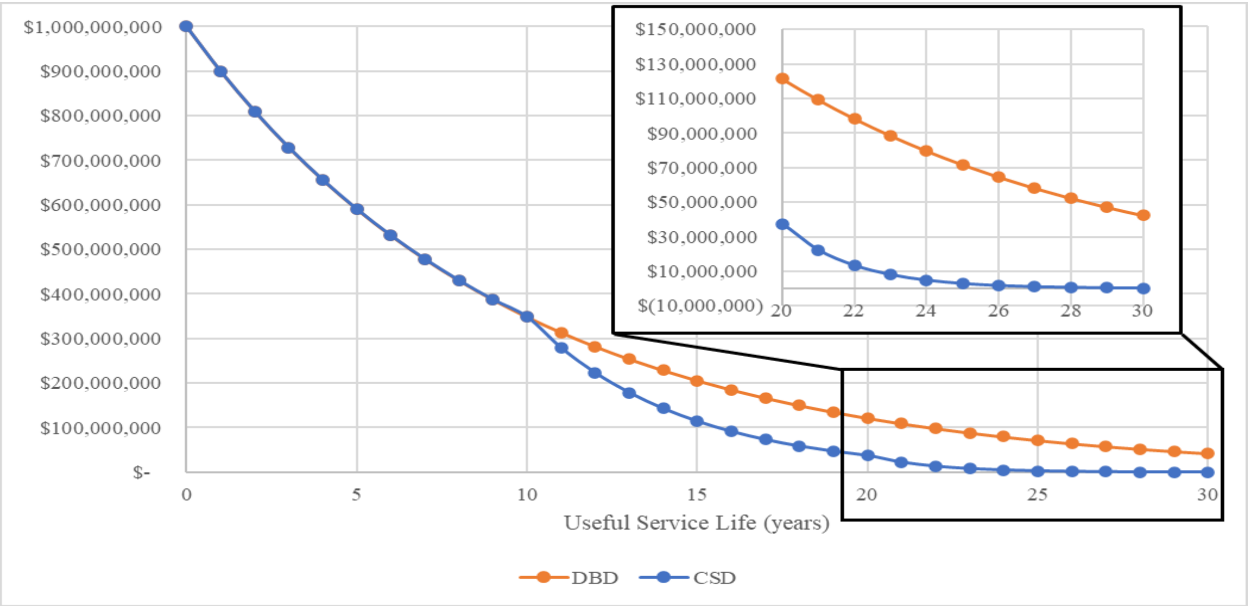


Figure 1 - Salvage Value with Respect to Time

While this is only part of the picture it does start to bring into the focus the financial side of the discussion. In short how much will the proposed upgrade cost versus the cost of the vessel. This starts to drive at a fundamental question that should be asked before a system upgrade commences. Is it worth the expense given the current value of the asset? It is acknowledged that salvage value is an artifice of economics, just because an asset has zero value on the books doesn't mean that it has no capability. Specifically in the context of working ships and military vessels capability is often the point. So, if the upgrade passes the initial cost-based litmus test, then the conversation returns to cost versus capability. While this gets more subjective there are some basic ground rules that should be employed. Consider a 4x4 grid with Additional Capability on the horizontal axis and Impact of Addition on the vertical axis. Then each block would roughly represent quartiles. The low end of the Additional Capability scale would be replacement in kind systems or software upgrades. The high end of this scale would be wholly new capabilities such as new weapons systems, launch and recovery systems, or automation approaches. The low end of the Impact of Addition could be bolt on systems that do not require an availability in a shipyard. The high end of this scale is a multi-year yard period with a complex or total overhaul. With these end posts, Quadrant 1 would represent high installation impact for a minimal capability increase. This is largely an area to be avoided for maximizing end product capability. Quadrant 2 would represent high installation impact but the addition of a potentially game-changing new capability. Quadrant 3 has low installation impact with a minimal capability increase. This leaves Quadrant 4; low installation impact and significant capability increase. Quadrant 4 is the optimist's corner, high payoff with low cost. Upgrades that fall into this area should be executed once they pass the previous financial screening. Figure 2 below summarizes this construct.

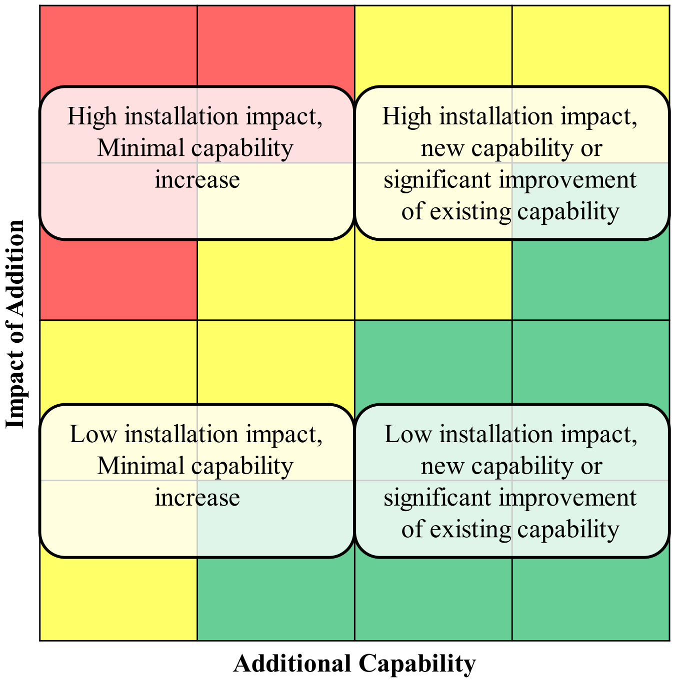


Figure 2 - Capability - Impact Scoring

"Note that while there has been considerable progress in maturing technology, no single technology has successfully met all the criteria for being institutionalized." (Doerry, 2014) In Figure 3 it can be seen how the total ship effectiveness is maintained and augmented by individual system additions across a span of 25 years. In this case since the design interface standard was locked to a MK41 Vertical Launch System incremental improvement was possible as technology matured across the complete system. However, if there was not a definitive standard such as the MK41 this story may have been much less compelling, this is also supported by historical development.

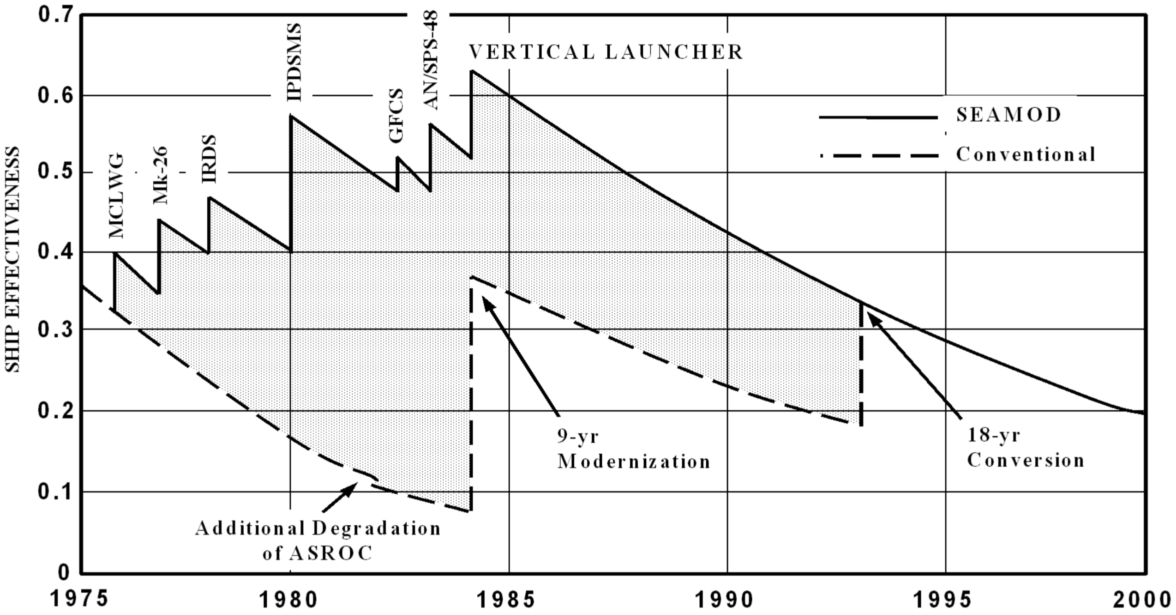
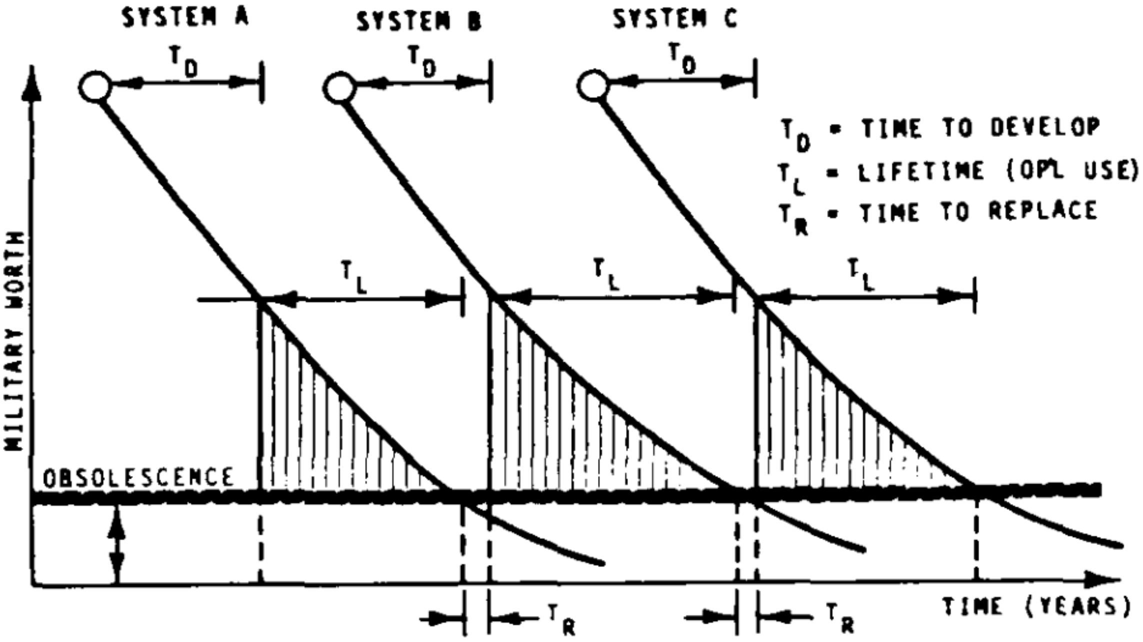
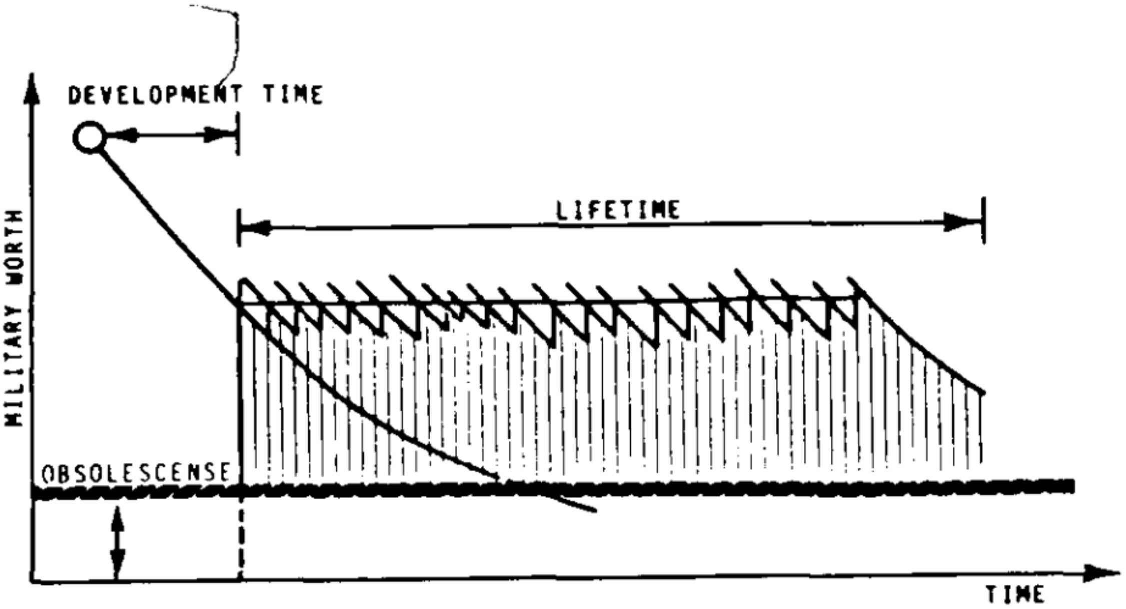


Figure 3 - Ship Effectiveness: SEAMOD vs Conventional (Abbott, 2006)



A. MODERNIZATION VIA SYSTEM REPLACEMENT



B. INCREMENTAL MODERNIZATION AT THE COMPONENT LEVEL

Figure 4 - Incremental Modernization Prior to Systems Obsolescence (DREWRY, 1975)

Figure 4 - Incremental Modernization Prior to Systems Obsolescence (DREWRY, 1975) illustrates an idealized scenario in which “incremental modernization at the component level” are made on a consistent basis to maintain the overall “military worth” of the vessel across the service life of the ship. This is proposed in contrast to the “modernization via system replacement” approach. The challenge with this approach is it requires an immense amount of consistency across the life of the class, and it assumes a linear technology growth path. Both are potentially flawed assumptions.

This section has looked at what system modifications should be entertained based upon the capability enhancement and the impact of installation, what are the alternative fielding strategies for modifications, and an example of incremental upgrades in a fielded system. This sets up the next discussion point.

HOW DOES AN ARCHITECTURAL STANDARD DEVELOP TO SUPPORT SUSTAINED MODULARITY?

The US Navy has had sporadic efforts related system level modularity in naval vessels since 1972. (Schank et al., 2016) The following bullets provide a synopsis of US Navy efforts in the establishment of a modular architectural standard.

- 1972 – 1978: Sea Systems Modification and Modernization by Modularity (SEAMOD)
    - Focused on modularized combat systems
    - Results were encouraging but required an overhaul of business and design practices
    - DD963 (com. 1975) and FFG7 (com. 1977) baseline ships under evaluation
- 1980 – 1985: Ship Systems Engineering Standards (SSES)
    - Focused on interface standards and variable payload systems
    - DDG51 (com. 1991) was the baseline for this effort
- 1992 – 2003: Affordability Through Commonality (ATC)
    - Focused on the reduction of acquisition and life cycle cost
    - Fleetwide implementation vice specific baseline
- 1994 – 2004: Open Systems Joint Task force (OSJTF)
- 1998 – 2003: Total Ship Open systems Architecture (TOSA)
- 2003: Open Architecture Computing Environment (OACE)
- 2003 – 2015: Architectures, Interfaces, and Modular Systems (AIMS)
    - Focused on a future implementation of modularity vice a backfit scenario

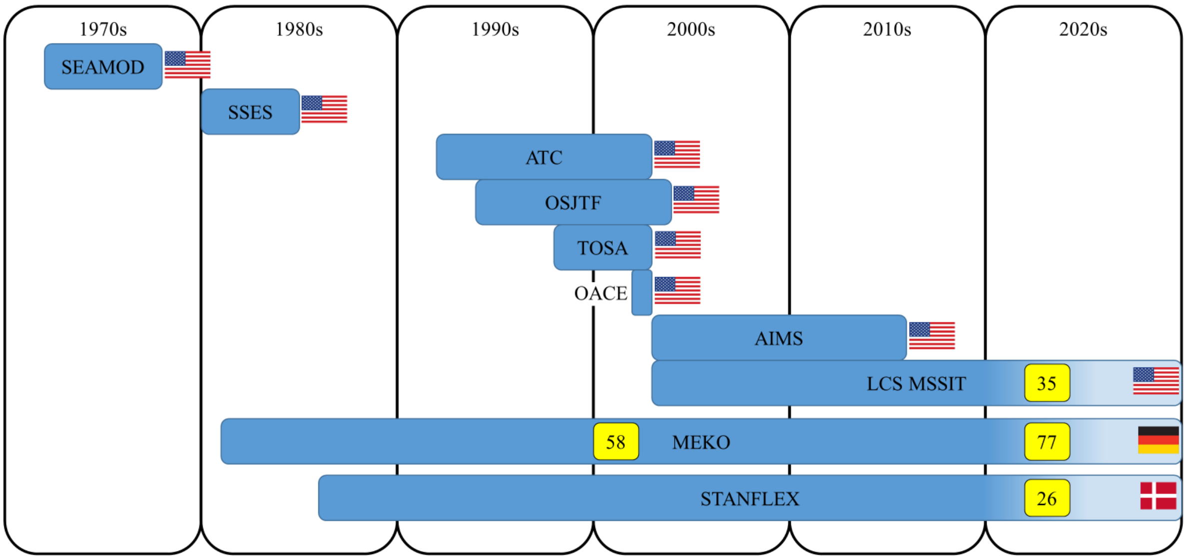


Figure 5 - Global Modular System Efforts (Strickland, 2023)

"The DDG 51 Class, which was supposed to be limited to 8,300 tons full load to show it was smaller than the preceding CG 47 cruiser class, was not fitted with extensive modularity for that reason. Only the 2 VLS weapons were built to Ship Systems Engineering Standards (SSES) Interfaces." (Garver et al., 2011)

Figure 5 illustrates to scale, the time span of efforts of the US Navy, Thyssen Krupp Marine Systems (TKMS) Mehrzweck-Kombination (MEKO) (Thyssen Krupp Marine Systems, n.d.), and Royal Danish Navy (RDN) Standard Flex (STANFLEX) (Harboc-Hansen, 1992), while this does not represent the total volume of funding expended it does begin to illustrate two key points. The first is that a steady state development absent of temporal breaks produces better results in terms of number of full systems delivered. The second is that there is not a single approach. Both the US Navy and the RDN have subscribed to an encapsulated subsystem that can be removed and replaced depending on the platform mission set and the need at present. This contrasts with the TKMS MEKO system that has less overall flexibility but creates standardized "sections" to produce vessels in support of customer requirements. This approach of modularized sections has been well received on the global market with 2-3 times the number of ships produced above encapsulated subsystems. The numbers in the yellow boxes on Figure 5, represent the total number of vessels delivered with these inherit features. This is somewhat misleading because the MEKO vessels are full systems complete with associated combat systems, and in some cases for the US Navy and RDN vessels the combat systems is dependent upon the installation of a mission module governed by a separate procurement. (Piñeros Bello & Segovia Forero, 2020) This construct of decoupled weapon systems and vessel design is not novel. The basic premise of allowing each to progress along a desired development path and then integrate them also brings a series of opportunities and challenges.

WHY HAVE MODULARITY EFFORTS FAILED TO DATE?

It is hard to discuss system level modularity without being drawn to the IT sector. In order to illuminate this critical question, I will begin this section with a personal anecdote. When I first started buying my own computers in the late 1990s, I realized that the rate of development and change was hard to keep pace with and there was the balancing act of being a cash strapped college student. As such I chose a tower chassis that had several expansion slots for additional RAM and PCI cards. In turn I continued to upgrade that machine utilizing the system level "modularity" of the PC market. After a RAM upgrade, a HDD, a sound card, a video card, and a modem, I reached the functional limit of the machine. While the process of upgrading a machine was gratifying, after the fact I still needed to replace it. While I continued to increase the relevance of the machine over time the cost of the upgrades was clearly in excess of the total cost of a machine that had these upgrades at the beginning. Further once you factor in the personal time in trouble shooting software compatibility issues it was far cheaper to purchase the end product at the beginning. This is the first axiom of modular systems. The cost over time of the end item is greater utilizing modular upgrades than the initial purchase cost of an upgraded system.

But there was a larger failed premise underlying this learning exercise. The machine was going to continue to be relevant even after all possible upgrades had been made. While the interface standards remained consistent during the personal example above, and many of those standards are still in use almost 30 years later the incremental upgrades could not keep pace with the component rate of change. I believe that this is one of the fundamental sources of failure in total system level modularity.

While interface standardization and commitment are necessary conditions, they are not fully sufficient for successful implementation on modularized systems. Even with the necessary conditions met one needs to balance the cost vs the capability of the system upgrade. Back to the PC example, if it is determined that the service life of the machine is five years, this adds a context to support the tradeoff of cost versus capability. With the addition of Moore's Law, it can be shown that within the five-year service life of the machine, the industry standard computing power quadrupled. So, the question becomes is the cost of the upgrade going to increase the relevance of the total system to a point that is on par with the current industrial standard. The answer is unfortunately no. While the modular upgrade may add a new capability or even improve an existing capability it will not be competitive with the current market standard.

This brings us to the second axiom of modular system failure; piece meal system acquisition will never keep pace with the developmental capability of new production. The computer growth issue highlighted by Moore's Law is just one component of total system level capability maturation scheme. This axiom has transcended computer systems into mechanical systems at this point. The automobile industry is a great example of the last point. New vehicles have hundreds of processors and are incapable of operation if the Electronic Control Unit is offline. (Charette, 2021)

HISTORICAL ANALOGY: AGE OF SAIL AND MARINE ARTILLERY

During this 400-year period of history it is the height of European colonialism, a great power competition, and a technological development race. The renewed focus on scientific pursuits from the Renaissance and the Great Enlightenment ultimately culminated in the Industrial Revolution. This is the backdrop for the historical analogy. See Figure 6 - Timeline of key developmental events.

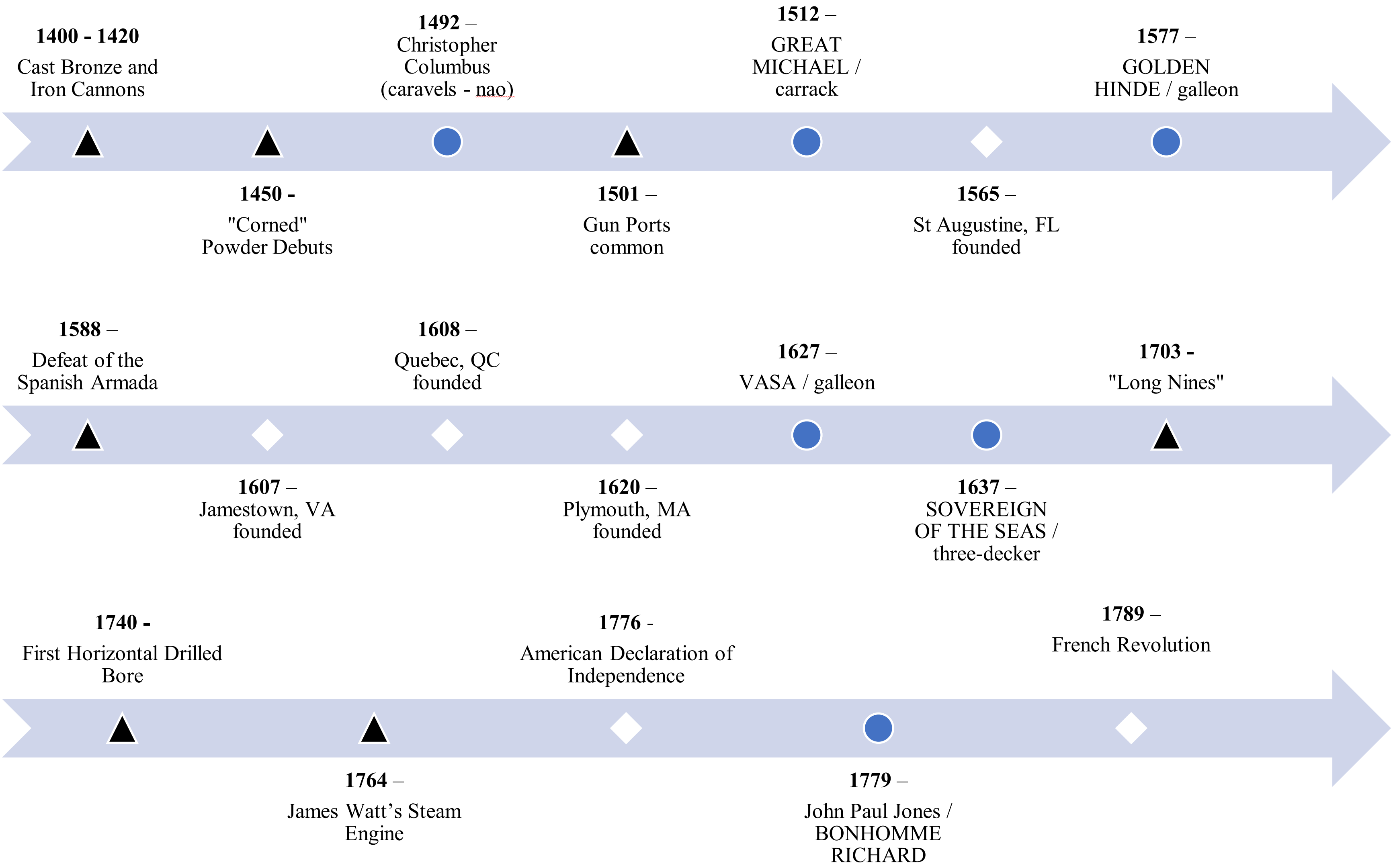


Figure 6 - Timeline of key developmental events; In the above figure entry symbols represent the following: ▲ technological advancements that influenced maritime system development; ● significant vessels discussed within the context of this paper; ◇ major geopolitical events that impacted naval systems and maritime system development

European Colonialism

For this discussion the colonialization of North America is representative of the broader world stage. On Figure 6 there are six events represented by a diamond. The first four of these events represents the establishment of permanent settlements in North America by the Spanish, English, and French. St Augustine (Spanish) (*Our History | St. Augustine, FL*, 2023), Jamestown (English) (US National Park Service, 2022), and Quebec (French) (Mendel, 2022) were the new focal points in a struggle between these three countries that dated back hundreds of years at this point. The founding of Plymouth, MA is interesting for several reasons. First the MAYFLOWER was a hired transit, while they did need permission to build a colony it was not strengthen the position of the European Monarchs via trade routes and raw materials. The final two diamonds are the American and French Revolutions. These resulted in massive changes to the geo-political fabric of the time and helped to fuel the great power competition underway by destabilizing the established order.

Technological Development Race

To continue to support the competitive nature and massive expansionism, new technologies were being developed and fielded almost constantly. Any advantage or technological edge could make an enduring difference in the power race. From a naval perspective two technology trends need to be discussed, the advancement of sailing ships and marine artillery. These technology milestones are marked by circles or triangles respectively, see Figure 6.

"During the Hundred Years' War (1339-1453) cannons came into general use. Those early pieces were very small, made of iron or cast bronze, and fired lead or iron balls. They were laid directly on the ground, with muzzles elevated by mounding up the earth. Being cumbrous and inefficient, they played little part in battle, but were quite useful in a siege." (Manucy, 1949) In the early part of the 15th century artillery manufacturing obtained a critical breakthrough, casting of iron and bronze of ever increasing size. (Dana, 1911) In this same timeframe the transition from a ground-based siege weapon to a naval weapon was well underway. (Devries, 1990) In fact by the turn of the 15th century, most English ships of any size were equipped with powder fired weapons. (Devries, 1990) It should be noted that these weapons were mounted on the topsides of the vessels and cannon/gun ports do not become prevalent until vessel construction moves away from clinker type hulls. The technological advance of casting muzzle loading cannons is met with the development of corned powder, "corned powder develops its propulsive force far more quickly than a tightly packed charge of dry-mixed, or serpentine, powder" (Guilmartin, 2007) This massive increase in the effectiveness and consistency of gunpowder allowed for greater range and control of the combustion in support of artillery operations.

On the timeline this brings us to Columbus' voyage to North America, possibly one of the most fortuitous mistakes of history. But the focus for this discussion is on the three vessels utilized in the 1492 crossing. The Nina, Pinta, and Santa Maria were two caravels and a carrack / nao, respectively. The caravel class of vessel began to use carvel construction approach vice the previous clinker type hulls. These smoother hulls proved durable, agile, and faster than their rougher predecessors. This is largely why the caravel became a popular platform for exploration and trade. Figure 7 illustrates a model of a caravel likely in a typical rigging pattern. The caravel's prominence was supplanted by the larger carrack. Larger in every dimension the carrack was like a caravel in construction with the addition of a focsle. Figure 8 illustrates the squared rigged sails forward with the prominent focsle. These vessels maintained the aft lateen sail.

Figure 7 - Three masted caravel with lateen rigged sails (Deutsches Historisches Museum, n.d.-a)

Figure 8 - Three masted carrack / nao with square rigged sails forward and lateen sail aft

With carvel construction as the dominating European approach, smooth hulls with carefully carved butt joints between planks affixed over a series of deep frames, the stage was set for the next advancement in naval artillery. The relocation of guns from the topside is largely due to the advent of gun ports. By the early 1500's gun ports were a predominant feature in naval designs. (Skaarup, 2021) The GREAT MICHAEL (Newhaven Heritage Centre, n.d.) and the MARY ROSE (Mary Rose Trust, 2023), both launched 1511, featured extensive armament via gunports below the weather deck.

As the GREAT MICHAEL and the MARY ROSE began to maximize the capacity of the carrack, the next evolutionary step was devised in the platform. The galleon's length was increased to support an additional mast and provide better seakeeping and resistance characteristics without a reduction in cargo fraction. (Deutsches Historisches Museum, n.d.-b; Mariners' Museum and Park, 2023). These vessels were specifically designed to support military operations and open ocean transits. "The Golden Hind, an English galleon launched in 1577 and best known for her privateering circumnavigation of the globe between 1577 and 1580, captained by Sir Francis Drake" (National Historic Ships UK, 2023) is a great example of this design marriage. The purpose of Golden Hind was to sail the oceans and raid Spanish settlements further supporting the building international competition to colonize the globe. Upon Drake's return tensions between the English and Spanish were at an all-time high. These tensions culminated with the English defeat of the Spanish Armada. This historical milestone was not solely predicated on technological advancements but on the employment of innovative new tactics. "In 1588, Spain's King Philip II ordered a naval invasion of England. Philip's Spanish Armada of 124 ships, 27,000 men, and 1,100 guns departed from Lisbon on May 30, 1588. England meanwhile, led by Queen Elizabeth I, readied a counterforce of 197 vessels, 16,000 men, and 2,000 guns." (Adams, n.d.) The English had the advantage of numbers in ships, but they were smaller and more agile than the landing force galleons employed by Spain. A fundamental shift in tactics made all the difference in the outcome. "To the Spanish, ships were floating fortresses to be grappled and taken at sword's point, but to the English, they were fast and maneuverable gun platforms." (Niderost, 2007) This new style of naval combat, maintaining a standoff and pummeling your opponent with gun fire, remains a prevalent tactic. We have however just increased the standoff distance and engagement speed with missiles. This decisive victory cemented the cannon's place in naval artillery as a ship-to-ship weapon not just a tool for shore bombardment.

The first half of the 17th century is marked by another expansion of platforms to support naval artillery and longer sailing distances at speed. The ship of the line had become the preferred battle tactic and quite often the vessel with the most guns won. Most vessels in this role during this time were galleons with one or more full gun decks. Let's look quickly at two such ships in the pivotal time. The VASA was a galleon, with a traditional design and a single gun deck. The original design was to carry thirty-two 24-pound guns. (Fairley, n.d.) During the construction revisions to the design added a second deck and another thirty-two 24-pounders (5,600 lb. / cannon). (Kessler et al., 2001) This raised her effective center of gravity. Further ships were a symbol of national pride and as such they were extremely ornate. This also created an increase in the center of gravity. The vessel's maiden voyage lasted 1,300 meters, before capsizing in 1628. The SOVEREIGN OF THE SEAS was a three-decker, meaning she carried three full gun decks. She had very similar ornate decorations and an increased capacity from her predecessors. The SOVEREIGN OF THE SEAS served in multiple campaigns from 1637-1696. (Holmes, 2010) Table 1 allows one to compare the principal characteristics of the VASA to the SOVEREIGN OF THE SEAS. One should note that there is only a decade between the launch dates of these vessels. Further the VASA would have been one of the most aggressively armed vessels of the time, although the SOVEREIGN OF THE SEAS had a 55% increase in the total number of cannons with a modest increase in total displacement. Finally, if the cannon designations seem confusing, it is because they are nonstandard. Every country at this time forged their own barrels and mass standardization of barrel length, bore diameter, shot weight, and other key attributes of marine artillery were not standardized until the middle of the 18th century. (Berkowitz & Dumez, 2016; Henry, 2009; Manucy, 1949) The end of the 18th century effectively marks the end of the golden age of sail. With the advent of the steam engine, and the further geopolitical unrest the stage was set for the next major development modification of platforms. This conjoined development process of weapon systems and platforms continues to this day. While there are almost endless volumes of historical examples that could be evaluated. Let's use the balance of the discussion to examine a few select modern corollaries considering this context.

Table 1 - Comparison of VASA to SOVEREIGN OF THE SEAS (Holmes, 2010; The Vasa Museum, 2015)

	Vasa	Sovereign of the Seas
LOA	155.8 ft	167 ft
Beam	38.4 ft	48.3 ft
Depth	63.3 ft	76 ft
Displacement	1210 tons	1683 tons
Armament	Lower Deck 28 x cannons (24 pdrs) Upper Deck 22 x cannons (24 pdrs) Weather Deck 2 x cannons (1 pdrs) 8 x cannons (3 pdrs) 6 x cannons (6 pdrs) Total 66	Lower deck 20 × cannon drakes (42-pdrs) 4 × demi-cannon drakes (32-pdrs) 2 × demi-cannon drakes (32-pdrs) 2 × demi-cannon drakes (32-pdrs) Middle deck 22 × culverin drakes (18-pdrs) 2 × demi-culverin drakes (9-pdrs) 4 × culverins (18-pdrs) 2 × culverins (18-pdrs) Upper deck 22 × demi-culverin drakes (9-pdrs) 2 × demi-culverins (9-pdrs) 2 × demi-culverins (9-pdrs) Quarter deck 6 × demi-culverin drakes (9-pdrs) Poop deck 2 × demi-culverin drakes (9-pdrs) Forecastle 8 × demi-culverin drakes (9-pdrs) 2 × culverin drakes (18-pdrs) Total 102

MODERN COROLLARIES

This section will discuss the development of two of the three modern modularity exercise highlighted in Figure 5. Specifically, the Littoral Combat Ship (LCS) and the Standard Flex (STANFLEX) efforts will be analysis for similarities and difference. The previous historical case study will be utilized for contextualization. The MEKO approach has been omitted from this conversation since the approach is dramatically different than that employed by the US and Danish Navies. Global componentization in construction should be further evaluated and the MEKO would be a beneficial case study in that endeavor.

Littoral Combat Ship

The Littoral Combat Ships was envisioned to be a high speed, inexpensive platform with a modular mission system that could be dynamically assigned in theater. "Rather than being a fully multimission ship like the Navy's larger surface combatants, the LCS is to be a focused mission ship, meaning a ship equipped to perform one primary mission at any given time. The ship's primary mission orientation can be changed by changing out its mission package, although under the Navy's latest plans for operating LCSs, that might not happen very frequently, or at all, for a given LCS." (O'Rourke, 2019) One potential performance issue with the disaggregated development and acquisition of the LCS Mission Packages was the fact that each Mission Package consisted of multiple Mission Modules. (Asst Secretary of Navy, Research, Development, and Acquisition, 2018) These Mission Modules had different developers and integrators. This is further confounded by the development and testing timeline associated with each Module at the sub-Package level. The result was "the total initial mission package operational capability has been delayed by about 9 years (from 2011 to 2020) and the Navy has lowered the level of performance needed to achieve the initial capability for two packages". (Francis, 2016) Further, "Changes in the LCS concept of operations are largely the consequence of less than expected lethality and survivability, which remain mostly unproven 7 years after delivery of the lead ships". (Francis, 2016) this brings us to the current scenario with 35 hulls being awarded in various stages of construction with two distinct variants. Despite the lapse of 21 years since program initiation, and almost 3 dozen ships, the reality of a hot swapable flexible combat system has fallen dramatically short of the initial vision.

Why did this effort fall so short of initial expectations? It is my feeling that there are two fundamental underlying contributors to these results. First, a lack of established standards. This total system acquisition effort undertook the development effort of two distinct sea frames, three mission packages, and the development of modular interfaces. This effort would have been challenging enough with a single sea frame, mission package, and associated interface standards. This challenge coupled with aggressive requirements created a scenario for the much-publicized difficulties of the LCS Program. Unlike the historical scenario above there was not a clear shipboard interface for independent development of modularized systems. The gun port, albeit simplistic, allowed for independent development of platforms and weapons and further facilitated the integration of these systems without major retrofits. The complexity of integrating a modern cannon or missile system is not lost here, however the point is that the interface standards did not exist prior to program initiation and these newly developed standards created in stride with the program development needed to accommodate a range of modules further increasing the total system complexity. Regarding system complexity this brings us to the second contributor, the hierarchical mission package – mission module – mission system construct adds a tremendous amount of requirement interdependency and thus increases the overall risk to execution. With three distinct Mission Packages each comprised of multiple modules and sub systems all being coincidentally independently developed by a variety of vendors the opportunity to encapsulated schedule risk and hedge performance characteristics is virtually nonexistent. A performance or developmental failure in a lower tier system would lead to cascading failures. This was realized with Surface-to-Surface Missile Module (SSMM), Remote Multi-Mission Vehicle (RMMV), and Dual-mode Array Transmitter (DART).

The SSMM was designed and tested with the AGM-114L Longbow Hellfire missile. This missile variant was actively produced until 2005 and is scheduled to be replaced with the AGM-179 Joint Air-to-Ground Missile (JAGM). Meanwhile the first successful land attack exercise was conducted with the Longbow Hellfire on 12MAY2022. (Hardgrove, 2022) While this is not a failure in the development of the SSMM it will mean the need to retest and potentially delay operational use of the module as it is being certified for the launch of another missile platform. The RMMV was somewhat operationally successful but unreliable. (Remote Minehunting System (RMS), 2016) After ship integration issues due to launch and recovery (FY15 Navy Programs - Remote Minehunting System (RMS), n.d.), two Nunn-McCurdy programmatic breaches (2009, 2015) (Eckstein, 2015), and failure to progress after a dedicated reliability improvement effort (FY15 Navy Programs - Remote Minehunting System (RMS), n.d.) the RMMV was officially canceled in 2016 (Remote Minehunting System (RMS), 2016). This realized failure in a critical system within the Mine Countermeasures (MCM) Mission Package required that the entire package be refactored and rearchitected. As such years of delay were experienced, in fact the MCM Mission Package just obtained its Initial Operational Capability in early 2023. (Shelbourne, 2023) The DART was optimized for weight considerations and modular employment within the LCS waterborne systems area of the mission bay. The prototypes were initially accepted in 2018 and then development was subsequently canceled in 2022. This cancelation was due to SONAR performance and reliability. (Abott, 2022; *Navy Canceled Raytheon's DART Sonar Due to High Risk | InsideDefense.Com*, n.d.) Given the above one can begin to see how the inability to encapsulate schedule and performance risks during the development created a realized risk in each of the Mission Packages for the 35 LCS sea frames.

STANFLEX

"The driver for StanFlex was money—the Royal Danish Navy needed to replace 22 warships of three classes, but it could not afford to do so on a one-for-one basis, so it came up with the idea of building 16 multirole modular vessels (later cut to 14)." (*Beware the Allure of Mission Modularity*, 2023) The basic assumption behind the STANFLEX concept was that "logistic standardization and operational flexibility can be achieved by use of rapidly exchangeable, modular systems matching a variety of roles" (Harboc-Hansen, 1992) Does this sound familiar? It should, it is the exact same justification that was utilized for the LCS program. So, the ultimate question becomes why the STANFLEX experience is considered successful and the LCS experience is considered painful. Maybe it is the scale of the effort, the complexity of the end system, or acquisition approach.

The first vessels to be outfitted with the STANFLEX modules were the Surface Auxiliary Vessel (Harboc-Hansen, 1992) later designated as the Flyvefisken Class (SF 300) ("Flyvefisken Class (SF 300)," n.d.). These composite vessels were of a size and complexity that supported a multitude of roles from MCM to environmental support and provided a perfect opportunity to work out the bugs associated with fielding a modular combat system. The length of the Flyvefisken is 54m, with four STANFLEX slots accounting for 12m of the vessels weather deck. In this initial case of modularization, the RDN allocated a smaller vessel than the LCS with a much higher percentage of modularization. The total scale of the initial effort is drastically different, but it allows for the required learning by the government and industry. The complexity of the ultimate end system and desired mission effectiveness could be the next key to success. Again, like the LCS the RDN had originally envisioned surveillance, combat, offensive mining, anti-pollution, anti-submarine warfare, and MCM mission packages composed of distinct modules. The biggest difference is that each of the modules all conformed to the same structural envelope and utilized standardized connections. This self-encapsulated module approach helps to mitigate performance and schedule risk associated with the concurrent development of the mission packages. Finally this brings us to an acquisition approach, Naval Team Denmark (*Https*, n.d.) is an industry and regulatory consortium that develops, and delivers the STANFLEX modules. It does make one wonder if the top 20 naval defense agencies in the US was to form a design and fabrication consortium that would have sufficiently altered the LCS experience. In this case the parallels to the historical case are enlightening. The RDN had a definitive fixed standard for modularized systems that was trialed on a small case and then eventually expanded to all following classes. This allows for consistent spiral development and compatibility. The ultimate complexity was managed starting with the least taxing cases and eventually evolving and increasing capability to account for more challenging configurations. And finally, this became a point of national pride. Much like the capital sailing vessels the defense conglomerate that was empowered around the STANFLEX project pulled the best from the industrial base to develop a successful program and new naval standard.

SUMMING UP

During the first section of this paper a more descriptive definition of modularity has been developed. This definition describes modularity along six continuums: 1) Componentization, 2) Architecture, 3) Configurability, 4) Flexibility, 5) Interface Points, and 6) Allocation. While the treatment of this definition is subjective in this document a more objective mechanism has been developed and is under evaluation at this time. An effort has been made to expose the underlying motivation and attractiveness of modularity in naval vessels utilizing economic salvage value and a less tangible ship effectiveness. Finally, the first section concludes with a look at investment duration by project for the last five decades relating to the development of architectural standards and why many modern modularity efforts have failed to produce the envisioned results. Culminating in two axioms of modular system failure: 1) the cost over time of the end item is greater utilizing modular upgrades than the initial purchase cost of an upgraded system, and 2) piece meal system acquisition will never keep pace with the developmental capability of new production.

The second and third section of this paper develop a historical analogy and review modern corollaries, respectively. Specifically with respect to the historical section the decoupling of platform and weapons system development allowed for gains in both systems since the interface point was a loose constraint. This concept of independent development allowed for each system to evolve based on technological limits and the application of new techniques. The maintenance of a loose interface standard allowed for frequent upgrades and modifications to occur on a timeline that made the most sense for system fielding. Additionally, developmental and schedule risk was encapsulated thus minimizing the total acquisition impact. The final section presented two modern modularized naval vessels considering these historical lessons learned. One program fell far short of it envision capability due to the lack of established standards, and a tremendous amount of requirements interdependency. While the second controlled the scale of the effort, the complexity of the end system, and applied a community-style acquisition approach. Even though the initial case of modularization was assigned to a much smaller vessel than the previous example, there was a much higher percentage of modularization.

While this is a quick survey of 50 years of modern system development spanning countless millions of dollars, supported by a case study that spans almost 300 years, the principal key to success in modular systems is the adoption and commitment to an interface standard that is not overly constrained. Historically the gun port allowed for the development of platform and weapon technology to be decoupled and developed independently. Similarly, the STANFEX fixed a geometric interface and has allowed for the iterative development of new combat and support systems to be developed and successively deployed across new classes. Modularity will continue to be attractive to naval vessels but to realize the potential of this modularity, a definitive standard must be adopted and employed uniformly across multiple classes.

SOURCES CITED

Abbott, J. W. (2006, April 27). *The History of Modular Payload Ships:*

Abott, R. (2022, September 1). *Navy Cites Reasons For Ditching DART Sonar For LCS, Frigate*. Defense Daily. https://www.defensedaily.com/navy-explains-challenges-of-canceled-dart-lcs-frigate-sonar/navy-usmc/

Adams, R. (n.d.). *The Spanish Armada, 1588*. Gilder Lehrman Institute of American History. Retrieved August 29, 2023, from https://www.gilderlehrman.org/history-resources/spotlight-primary-source/spanish-armada-1588

Asst Secretary of Navy, Research, Development, and Acquisition. (2018). *Report to Congress for the Littoral Combat Ship Mission Modules Program—Annual Report* (4–5617062). US Navy. https://news.usni.org/2018/04/03/littoral-combat-ship-mission-package-annual-report

ATO Depreciation Rates 2021 • Vessel. (2021, July 1). Australian Taxation Office (ATO) Depreciation Rates 2021. https://www.depreciationrates.net.au/vessel

Balka, E., & Wagner, I. (2006). Making things work: Dimensions of configurability as appropriation work. *Proceedings of the 2006 20th Anniversary Conference on Computer Supported Cooperative Work*, 229–238. https://doi.org/10.1145/1180875.1180912

Baresi, L., & Miraz, M. (2011). A Component-Oriented Metamodel for the Modernization of Software Applications. *2011 16th IEEE International Conference on Engineering of Complex Computer Systems*, 179–187. https://doi.org/10.1109/ICECCS.2011.25

Berkowitz, H., & Dumez, H. (2016). The Gribeauval system, or the issue of standardization in the 18th century. *GÉRER & COMPRENDRE - ENGLISH LANGUAGE ONLINE SELECTION*, *125*. https://www.annales.org/gc/GC-english-language-online-edition/2016/BERKOWITZ-DUMEZ.pdf

Beware the Allure of Mission Modularity. (2023, May 1). U.S. Naval Institute. https://www.usni.org/magazines/proceedings/2023/may/beware-allure-mission-modularity

Charette, R. (2021, June 7). *How Software Is Eating the Car—IEEE Spectrum*. https://spectrum.ieee.org/software-eating-car

Dana, C. E. (1911). Notes on Cannon-Fourteenth and Fifteenth Centuries. *Proceedings of the American Philosophical Society*, *50*(199). https://www.jstor.org/stable/984031

Deutsches Historisches Museum. (n.d.-a). *Caravel*. Retrieved August 28, 2023, from https://www.dhm.de/mediathek/en/ship-types/milestones-in-the-history-of-european-shipbuilding/05-caravel/?backlinkAnchor=content-127

Deutsches Historisches Museum. (n.d.-b). *Galleon*. Retrieved August 28, 2023, from https://www.dhm.de/mediathek/en/ship-types/milestones-in-the-history-of-european-shipbuilding/08-galleon/

Devries, K. R. (1990). A 1445 Reference to Shipboard Artillery. *Technology and Culture*, *31*(4), 818–829.

Doerry, N. (2014). Institutionalizing Modular Adaptable Ship Technologies. *Journal of Ship Production and Design*, *30*. https://doi.org/10.5957/JSPD.30.3.130038

DREWRY, J. T. (1975). MODULARITY: MAXIMIZING THE RETURN ON THE NAVY’S INVESTMENT. *Naval Engineers Journal*, *87*(2), 198–214. https://doi.org/10.1111/j.1559-3584.1975.tb03730.x

Eckstein, M. (2015, October 13). UPDATED: Navy Launches Independent Review of Littoral Combat Ship Remote Minehunting System. *USNI News*. https://news.usni.org/2015/10/13/navy-launches-independent-review-of-littoral-combat-ship-remote-minehunting-system-new-look-could-cause-more-testing-delays

Elmenreich, W. (2007). A Review on System Architectures for Sensor Fusion Applications. In R. Obermaisser, Y. Nah, P. Puschner, & F. J. Rammig (Eds.), *Software Technologies for Embedded and Ubiquitous Systems* (pp. 547–559). Springer. https://doi.org/10.1007/978-3-540-75664-4_57

Eschenbach, T. (2011). *Engineering Economy: Applying Theory to Practice* (3rd ed.). Oxford University Press. https://global.oup.com/us/companion.websites/9780199772766/student/pdf/Chapter12E2010.pdf

Fairley, R. (n.d.). *Why The Vasa Sank: 10 Lessons Learned*. Retrieved February 13, 2023, from https://faculty.up.edu/lulay/failure/vasacasestudy.pdf

Flyvefisken Class (SF 300). (n.d.). *Naval Technology*. Retrieved September 25, 2023, from https://www.naval-technology.com/projects/fly/

Francis, P. (2016). *Littoral Combat Ship and Frigate—Congress Faced with Critical Acquisition Decisions* (GAO-17-262T). Government Accountability Office. https://www.gao.gov/assets/gao-17-262t.pdf

FY15 Navy Programs—Remote Minehunting System (RMS). (n.d.). Director, Operational Test and Evaluation. https://www.dote.osd.mil/Portals/97/pub/reports/FY2015/navy/2015rms.pdf?ver=2019-08-22-105645-710

Garver, S., Marcantonio, R., & Sims, P. (2011). *Modular Adaptable Ship (MAS) Total Ship Design Guide for Surface Combatants.pdf*. NAVSEA.

Guilmartin, J. F. (2007). The Earliest Shipboard Gunpowder Ordnance: An Analysis of Its Technical Parameters and Tactical Capabilities. *The Journal of Military History*, *71*(3), 649–669.

Harboc-Hansen, H. (Ed.). (1992). *Standard Flex 300*. Danyard. http://www.marinehist.dk/orlogsbib/h/StanFlex.pdf

Hardgrove, S. (2022, May 12). *LCS Successfully Completes First Land Attack Missile Exercise*. Naval Surface Force, U.S. Pacific Fleet. https://www.surfpac.navy.mil/Media/News/Article/3033364/lcs-successfully-completes-first-land-attack-missile-exercise/http%3A%2F%2Fwww.surfpac.navy.mil%2FMedia%2FNews%2FArticle%2F3033364%2Flcs-successfully-completes-first-land-attack-missile-exercise%2F

Henry, N. C. (2009). *Analysis of Armament from Shipwreck 31CR314: Queen Anne's Revenge Site* (QAR-B-09-01). Department of Cultural Resources, State of North Carolina. www.qaronline.org

Holmes, G. (2010). *Ancient and Modern Ships. Part 1. Wooden Sailing Ships*.

Https://navalteam.dk/members/. (n.d.). Retrieved September 25, 2023, from https://navalteam.dk/members/

Kessler, E., Bierly, P., & Gopalakrishnan, S. (2001). Vasa syndrome: Insights from a 17th-century new-product disaster. *Academy of Management Executive*, *15*(3), 80–91.

Kubota, F. I., Hsuan, J., & Cauchick-Miguel, P. A. (2017). Theoretical analysis of the relationships between modularity in design and modularity in production. *The International Journal of Advanced Manufacturing Technology*, *89*(5), 1943–1958. https://doi.org/10.1007/s00170-016-9238-4

Lafou, M., Mathieu, L., Pois, S., & Alochet, M. (2016). Manufacturing System Flexibility: Product Flexibility Assessment. *Procedia CIRP*, *41*, 99–104. https://doi.org/10.1016/j.procir.2015.12.046

Manucy, A. (1949). Artillery Through the Ages: A Short Illustrated History of Cannon, Emphasizing Types Used in America. *National Park Service Interpretive Series*, *3*. http://npshistory.com/series/interpretive/3/is3toc.htm

Mariners' Museum and Park. (2023). *Galleon—Ages of Exploration*. https://exploration.marinersmuseum.org/watercraft/galleon/

Mary Rose Trust. (2023). *The History of the Mary Rose: 1510-1545*. The Mary Rose. https://maryrose.org/the-history-of-the-mary-rose/

Mendel, D. (2022, April 19). *History of Québec City | Visit Québec City*. https://www.quebec-cite.com/en/quebec-city/history-quebec

National Historic Ships UK. (2023). *The Golden Hinde*. National Historic Ships. https://www.nationalhistoricships.org.uk/page/golden-hinde-london

Navy canceled Raytheon's DART sonar due to high risk | InsideDefense.com. (n.d.). Retrieved September 25, 2023, from https://insidedefense.com/insider/navy-canceled-raytheons-dart-sonar-due-high-risk

Newhaven Heritage Centre. (n.d.). *The Great Michael*. Newhaven : A Stravaig through Time. Retrieved August 28, 2023, from https://www.newhavenstravaigs.scot/locations/19-andrew-wood-court/the-great-michael/

Niderost, E. (2007, June). Defeat of the Spanish Armada. *Military Heritage*, *8*(6), 60–67.

O'Rourke, R. (2019). *Navy Littoral Combat Ship (LCS) Program: Background and Issues for Congress* (RL33741). Congressional Research Service. https://crsreports.congress.gov/product/pdf/RL/RL33741/257

Our History | St. Augustine, FL. (2023). City of St Augustine. https://www.citystaug.com/693/Our-History

Piñeros Bello, L. A., & Segovia Forero, C. E. (2020). Evolution and Present of Modularity in Warships. In V. A. J. E. Carreño Moreno, A. Vega Saenz, L. Carral Couce, & J. Saravia Arenas (Eds.), *Proceeding of the VI International Ship Design & Naval Engineering Congress (CIDIN) and XXVI Pan-American Congress of Naval Engineering, Maritime Transportation and Port Engineering (COPINAVAL)* (pp. 201–210). Springer International Publishing. https://doi.org/10.1007/978-3-030-35963-8_17

Remote Minehunting System (RMS) (DD-A&T(Q&A)823-286; Selected Acquisition Report (SAR)). (2016). Defense Acquisition Management Information Retrieval. https://www.esd.whs.mil/Portals/54/Documents/FOID/Reading%20Room/Selected_Acquisition_Reports/FY_2015_SARS/16-F-0402_DOC_75_RMS_DEC_2015_SAR.pdf

Schank, J., Savitz, S., Munson, K., Perkinson, B., McGee, J., & Sollinger, J. (2016). *Designing Adaptable Ships: Modularity and Flexibility in Future Ship Designs*. RAND Corporation. https://doi.org/10.7249/RR696

Shelbourne, M. (2023, May 12). Navy Talks Details on LCS Mine Countermeasures Mission Package. *USNI News*. https://news.usni.org/2023/05/12/navy-talks-details-on-lcs-mine-countermeaures-mission-package

Skaarup, H. (2021). *Artillery in Portugal: Lisbon, Museu Militar de Lisboa (Portuguese Army Military Museum of Lisbon) 1*. https://silverhawkauthor.com/post/artillery-in-portugal-lisbon-museu-militar-de-lisboa-portuguese-army-military-museum-of-lisbon-1

Strickland, J. D. (2023). Design Considerations for Unmanned Surface Vessels in Naval Service. *Journal of Ship Production and Design*, 1–11. https://doi.org/10.5957/JSPD.10220025

The Vasa Museum. (2015, October 17). *Vasa in numbers*. https://web.archive.org/web/20151017033410/http://www.vasamuseet.se/en/The-Ship/Vasa-in-numbers/

Thyssen Krupp Marine Systems. (n.d.). *Our Surface Vessels*. Retrieved August 21, 2023, from https://www.thyssenkrupp-marinesystems.com/en/products-services/surface-vessels

US National Park Service. (2022, September 16). *A Short History of Jamestown—Historic Jamestowne Part of Colonial National Historical Park*. https://www.nps.gov/jame/learn/historyculture/a-short-history-of-jamestown.htm